Seasonal and diurnal variations of near-surface atmospheric CO₂ concentration within a residential sector of the urban CO₂ dome of Phoenix, AZ, USA

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Abstract

Over most of an entire year (315 days), we obtained 1-min averages of near-surface (2-m height) atmospheric CO₂ concentration, temperature and wind speed in a residential area of a suburb of Phoenix, AZ. Daily minimum CO₂ concentrations, which occurred during the afternoon, were nearly invariant over the year, averaging 390.2±0.2 ppm. Daily maximum CO₂ concentrations, however, which occurred at night, varied seasonally with the air temperature, exhibiting a mean peak of 490.6 ppm about 2 h before midnight during the coldest part of the year (December–January) and 424.3 ppm just before sunrise during the warmest part of the year (July–August). Reevaluating prior assessments of the strength of the urban CO₂ dome at the center of Phoenix, our results suggest a mean cold-season maximum there of 619.3 ppm, which is 67.4% greater than the rural background value. At our residential site, however, the mean cold-season maximum was only 32.6% greater than the surrounding rural mean. Averaged over the entire night, this enhancement dropped to 25.4% in the cold season and 10.9% in the warm season, while over the daylight period it averaged 10.5% and 10.1% in the cold and warm seasons, respectively. CO₂ concentrations were greater on weekdays than on weekends from 0415 to 0830 in the warm season and from 0445 to 1045 in the cold season. During peak morning traffic, the maximum weekday-weekend CO₂ differential was 35.9 ppm in the cold season and 22.0 ppm in the warm season. Published by Elsevier Science Ltd.

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1. Introduction

We have documented and mapped significantly enhanced near-surface (2-m height) atmospheric CO₂ concentrations over the city of Phoenix, AZ, USA and its surrounding suburbs, calling this phenomenon the urban CO₂ dome (Idso et al., 1998). Much like the urban heat island (Goward, 1981; Oke, 1982), this anthropogenic enhancement of the air’s CO₂ concentration is caused by human modification of the natural environment, primarily the burning of fossil fuels to produce energy and facilitate motorized transportation.

An important implication of the existence of the urban CO₂ dome is that cities may provide effective “natural laboratories” for certain global change impact studies. By itself, the elevated atmospheric CO₂ concentration of the urban CO₂ dome could be used to study the consequences of the well-known aerial fertilization effect of atmospheric CO₂ enrichment, which stimulates the growth of herbaceous plants by...
30-40% in response to a 300 ppm increase in the air’s CO₂ content (Kimbull, 1983) while it enhances the growth of woody species by 50-100% or more (Idso, 1999). Together with the impact of the urban heat island, the impact of the urban CO₂ dome could also be employed to determine how simultaneous increases in air temperature and CO₂ content—such as those envisioned by the intergovernmental panel on climate change for the planet as a whole over the next century or so (Houghton et al., 1996)—might affect vegetation, thus providing a unique opportunity to peer into earth’s future and assess some of the consequences of predicted environmental change.

In our quest to better elucidate the nature of the urban CO₂ dome and thereby facilitate such studies, we recently measured its strength over the greater Phoenix area at what we assumed were the approximate times of its daily maximum and minimum CO₂ concentrations: 0500–0600 and 1400–1500 h, respectively (Idso et al., 2001). Data for this project were gathered from automobiles traversing the city prior to sunrise and in the middle of the afternoon during 14 consecutive days of the coldest part of the year, when the urban CO₂ dome is most strongly expressed. What remains to be learned is what happens throughout the rest of the year and over a complete diurnal cycle. To obtain this knowledge, we thus devised and carried out the study described here.

2. Experiment

We established a permanent weather-monitoring station 2 m above a grass lawn in the backyard of the corresponding author, who lives within the greater Phoenix area ~0.6 km north of the region’s major east–west freeway and 3 km east of its major north–south freeway in the suburb of Tempe (Fig. 1). At this residential location, measurements of atmospheric CO₂ concentration, air temperature, relative humidity, and wind speed and direction were recorded at 5-s intervals and averaged over 1-min periods for the greater part of an entire year (1 January–31 December 2000).

Measurements of CO₂ concentration in air were made with the same equipment used in the second of our automobile transect studies of the greater Phoenix area (Idso et al., 2001): the Model LI-800 GasHound CO₂ gas analyzer (LI-Cor, Lincoln, NE). The temperature and

![Map of the Phoenix metropolitan area showing locations of the major freeways and the site of the atmospheric CO₂ concentration measurements (*)](image)

Fig. 1. Map of the Phoenix metropolitan area showing locations of the major freeways and the site of the atmospheric CO₂ concentration measurements (*).
relative humidity of the air were measured with a Model CS500 temperature and relative humidity probe (Campbell Scientific Inc., Logan, UT); while wind speed and direction were obtained from a Model 034A-L met one wind set (Campbell Scientific Inc., Logan, UT). Data from all instruments were stored in a CR10X Measurement and Control Module (also from Campbell Scientific) and downloaded at weekly intervals. At monthly intervals, calibration checks and adjustments of the instruments were performed at the US Water Conservation Laboratory in Phoenix, where primary CO₂ standards from the Matheson Co. (East Rutherford, NJ) were used to ensure proper operation of the CO₂ gas analyzer.

3. Results

Our 1-min averages of near-surface atmospheric CO₂ concentration exhibited considerable scatter throughout each day, yielding extreme maximum and minimum values that were not representative of mean maximum and minimum conditions. Hence, we worked with 30-min averages to develop the seasonal plots of daily maximum and minimum atmospheric CO₂ concentrations shown in Fig. 2. This data set is virtually complete, except for the period from day 259 to 307 of year, when the CO₂ gas analyzer malfunctioned and no data were obtained.

As is readily observed in Fig. 2, minimum values of near-surface atmospheric CO₂ concentration, which occur during afternoon periods of intense solar-induced convective mixing, are nearly invariant over the entire year, exhibiting a mean yearly value of 390.2 ppm with a standard error of only 0.2 ppm. The maximum atmospheric CO₂ concentration (which occurs at night), on the other hand, exhibits a strong seasonal cycle, with a well-defined minimum in July and August, when nighttime minimum air temperatures are at their yearly high: a long-term mean of 24.9°C for the July–August period vs. 19.8°C for June and 20.6°C for September (Schmidli, 1978). This inverse dependency of the daily maximum atmospheric CO₂ concentration upon daily minimum air temperature is portrayed explicitly in Fig. 3.

To illustrate the nature of the diurnal cycle of near-surface atmospheric CO₂ concentration at our measurement site, we computed mean CO₂ concentrations for each minute of the day for two different time intervals—the coldest 2-month period of the year (December–January) and the warmest 2-month period of the year (July–August)—obtaining the results portrayed in Fig. 4.

![Fig. 2](image1.png)

Fig. 2. Daily maximum and minimum values of 30-min averages of near-surface atmospheric CO₂ concentration over the course of year 2000.

![Fig. 3](image2.png)

Fig. 3. Daily maximum near-surface atmospheric CO₂ concentration (30-min averages) vs. daily minimum air temperature (30-min averages). Values for the 2 coldest months of the year (December–January) and the 2 warmest months of the year (July–August) are depicted by open circles and triangles, respectively.

![Fig. 4](image3.png)

Fig. 4. Mean diurnal courses of near-surface atmospheric CO₂ concentration (2-month averages of 1-min data) for the coldest two months of the year (December–January) and the warmest 2 months of the year (July–August).
There are several things to be noted about the results of Fig. 4. First, in neither the coldest nor the warmest period of the year does the mean diurnal course of near-surface atmospheric CO₂ concentration ever reach the mean yearly minimum value of 390.2 ppm displayed in Fig. 2. The reason for this dichotomy is that the daily minimum values of Fig. 2 occur at different times of the day on different days, so that for any specific 1-min "instant" in time, the 2-month average CO₂ concentration is always less extreme. The difference, however, is not large; the mean cold-season diurnal CO₂ oscillation only misses the 390.2 ppm "anytime" minimum by 1.7 ppm at 1614, while the mean warm-season diurnal CO₂ oscillation only falls short by 3.5 ppm at 1314.

Second, and for the same reason, the mean diurnal courses of near-surface atmospheric CO₂ concentration in the 2-month-long cold and warm seasons do not rise as high as the means of the "anytime" maximum values determined for these periods by the open-circle and open-triangle data points in Fig. 3, which yield mean "anytime" maximum values of 527.7 and 441.5 ppm for the cold and warm seasons, respectively. The cold-season diurnal CO₂ oscillation misses the mean "anytime" maximum by 31.1 ppm at \(\sim 2200\); while the warm-season diurnal CO₂ oscillation falls short by 17.2 ppm at about 0600.

Other notable features of Fig. 4 are the major similarities and differences between the overall time-courses of the cold- and warm-season diurnal CO₂ cycles. In terms of similarities, from about 1030 to 1230 the near-surface atmospheric CO₂ concentrations of the two seasons are essentially identical; and from 1230 to 1830 they are of the same general magnitude, although they experience small fluctuations that are mirror images of each other. From 1230 to a little past 1300, for example, the cold-season CO₂ concentration rises slightly, while the warm-season CO₂ concentration drops slightly. From that point in time until a little past 1600, these trends are reversed; while from there to about 1830 they are reversed again.

The most noticeable of these minor differences—the divergence in cold- and warm-season CO₂ trends between \(\sim 1400\) and 1630—likely is caused by differences in wind speed between the two times of year. As can be seen in Fig. 5, post-midnight wind speeds in the two seasons are fairly constant and comparable until about 1400, whereupon the warm-season wind begins to grow significantly stronger, importing air of slightly greater CO₂ concentration, as noted by Idso et al. (2001), from the direction of the two major freeways, i.e., from the south and west. As the wind continues to increase in speed beyond 1630, however, it begins to pull in air that has been mixed with more pristine rural air, which causes the atmospheric CO₂ concentration to decline from about 1630–1830, at which point the warm-season wind begins to subside, leading to the development of a weak air temperature inversion that causes the near-surface atmospheric CO₂ concentration to slowly rise through the night, as anthropogenic CO₂ emissions accumulate between the ground and the top of the inversion layer.

By far the greatest and most important differences in the cold- and warm-season diurnal CO₂ cycles occur at night and in the early morning, as may be readily seen by a cursory glance at Fig. 4. Averaged across each season's nighttime period, for example, the mean cold-season CO₂ concentration is 464.1 ppm, while the mean warm-season CO₂ concentration is 410.4 ppm. This difference, of course, is due to the much greater strength and frequency of air temperature inversions in the coldest part of the year. Inversions at this time are normally present about 72% of the time, with fully 90% of them lasting until 1000; while they are normally present only 16% of the time in the warm-season, with only 18% of them lasting as late as 0000 (Idso and Kangieser, 1970).

The tremendous rise in the cold-season CO₂ concentration that begins just after 1600 is associated with that season's much shorter daylight and the consequent earlier development of its evening air temperature inversion, which begins to form about the same time the major afternoon peak in freeway-traffic starts to decline (Fig. 6). There is also a significant drop in the cold-season wind speed that begins at 1600. Consequently, with great volumes of CO₂ being emitted from vehicles into a calm, developing inversion layer, the near-surface atmospheric CO₂ concentration rises so rapidly that the peak of the diurnal CO₂ cycle actually occurs in the evening at \(\sim 2200\), rather than just before dawn, as in the warm season.

All else being equal, one would have expected the air's CO₂ concentration to continue to increase through the rest of the night, much as it does in the warm season. In the cold season, however, the surface wind speed—which is at its all-day low during the period of rapid near-surface atmospheric CO₂ buildup between 1800
and 2100—begins to increase and also switch directions just before the peak CO₂ concentration is reached, returning to come predominantly from the east. This new flow regime brings an infusion of lower-CO₂-content air from eastern and slightly northern rural areas; and together with much reduced and still declining vehicular traffic (Fig. 6), it drives the near-surface atmospheric CO₂ concentration to lower and lower values until just after 0400, when the first signs of the early morning traffic surge appear (Fig. 6). Then the near-surface atmospheric CO₂ concentration once again rises, recouping 29.9 ppm of the 50.3 ppm loss it experienced between 2156 and 0427. By 0745, however, solar-induced mixing of the lower layers of the atmosphere becomes so strong that the near-surface atmospheric CO₂ concentration plummets rapidly towards its typical low midday values, in spite of high traffic volume throughout the midday period (Fig. 6).

With as much data as we collected, we were also able to detect weekday-weekend differences in near-surface atmospheric CO₂ concentration at our measurement site. Over most of the diurnal period, these differences were insignificant in both the cold and warm seasons of the year. During early morning “rush hour” traffic, however, weekday CO₂ concentrations were definitely greater than weekend values. In the warm season, the maximum differential was 22.0 ppm at 0709, while in the cold-season it was 35.9 ppm at 0747. Also, a positive weekday-weekend CO₂ differential was maintained for about four and a quarter hours, from 0415 to 0830, in the warm season; while in the cold season it was maintained for about 6 h, from 0445 to 1045.

4. Discussion

Our observations suggest we may have greatly underestimated the maximum strength of the urban CO₂ dome in the central part of Phoenix in our prior cold-season vehicular transect study (Idso et al., 2001). The data of that study were obtained between 0500 and 0600 in the morning, which we had assumed would be the time of occurrence of the maximum near-surface atmospheric CO₂ concentration, which it truly is in the warm part of the year. It is clear from the results of Fig. 4, however, that the true cold-season maximum occurs at about 2200 in the evening at our site; and it likely occurs at that time in central Phoenix as well. In addition, the 0500 to 0600 time period does not even coincide with the cold-season morning traffic-induced peak in near-surface atmospheric CO₂ concentration, which occurs between 0700 and 0800. In fact, the 0500–0600 period comes very close to the time of occurrence of the cold season’s early morning minimum CO₂ concentration, which occurs about 0430.

Reevaluating our earlier work on the basis of these observations, we calculate from the cold-season diurnal CO₂ trend of Fig. 4 that, relative to the mean rural CO₂ concentration of 370 ppm, the urban-produced “excess” CO₂ concentration at 2200 is 1.56 times greater than what it is at 0530. Hence, multiplying the excess CO₂ concentration we measured at the center of Phoenix between 0500 and 0600 in our earlier study—159.8 ppm (Idso et al., 2001)—by this factor (1.56), we obtain a revised central Phoenix excess CO₂ concentration of 249.3 ppm, which when added to the rural base value of 370 ppm yields a new estimate of 619.3 ppm for the mean cold-season maximum CO₂ concentration at the center of the urban CO₂ dome of Phoenix. This new value is fully 67.4% greater than the rural background value, which is comparable to the degree of atmospheric CO₂ enrichment provided in many studies of the biological consequences of elevated CO₂.

Although the maximum strength of Phoenix’s urban CO₂ dome is truly amazing, its intensity drops off rapidly with distance from the center of the city. At our site, for example, which is 21 km southeast of the where the air’s CO₂ concentration peaks, the urban-induced increase in the cold-season’s average maximum CO₂ concentration is less than half as great as that experienced at the center of the CO₂ dome, averaging 32.6%. Averaged over the entire night, the urban-induced CO₂ enhancement at our site drops even further, to 25.4% in the cold season and 10.9% in the warm season; while during daylight hours it is smaller still, averaging 10.5% in the coldest part of the year and 10.1% in the warmest part.

Within the majority of the residential areas of Phoenix and its suburbs, it thus appears that the aerial fertilization effect of the urban CO₂ dome is likely not yet very large. Nevertheless, the urban complex provides a wide range of CO₂ environments that could prove useful—as we have previously suggested (Idso et al., 1998, 2001)—in exploring the biological consequences of...
the ongoing rise in the air’s CO₂ content. However, the center of the city would need to be closely approached to fully exploit this research opportunity; and in that area potentially higher concentrations of certain air pollutants might prove a confounding factor.

5. Conclusions

Our research has identified and defined the major characteristics of the urban CO₂ dome of Phoenix, AZ, the primary source of which is CO₂ derived from vehicular exhaust. It has also demonstrated that the primary controlling factors of the strength of the CO₂ dome are (1) the presence of air temperature inversions at night and in the early morning, which inversions trap vehicular-generated CO₂ near the ground, increasing its concentration there, and (2) solar-induced convective mixing during the mid-day period, which greatly dilutes the air’s CO₂ content near the ground. Secondary controlling factors are wind speed and direction in relation to sources of CO₂ (freeways and major roads) and areas of pristine rural air. Changes in these controlling factors occur on both diurnal and seasonal timescales, such that nighttime and winter urban CO₂ concentrations are generally much greater than daytime and summer concentrations.

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